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EXPERIMENTS RELATED TO EXTERNAL BURNING FOR PROPULSION.(U)

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AFOSR Final Scientific Report

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Experiments Related to External Burning for Propulsion

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Bolling Air Force Base, D. C.

by

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An experimental study of base flows for a 2.25 inch diameter projectile at Mach 3 with cold air injection is reported. Upstream radial jet injection and base injection are used. The work is a continuation of a systematic study of many of the flow field features of external burning. It is shown that radial jet injection alters the wake structure, shortens the wake, and reduces the base pressure. In addition, the advantage of base injection using porous base bleed diminish with injection rate and external compression.

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Abstract

An experimental study of base flows for a 2.25 inch diameter projectile at Mach 3 with cold air injection is reported. Upstream radial jet injection and base injection are used. The work is a continuation of a systematic study of many of the flow field features of external burning. It is shown that radial jet injection alters the wake structure, shortens the wake, and reduces the base pressure. In addition, the advantage of base injection using porous base bleed diminish with injection rate and external compression.

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I. INTRODUCTION

In prior work[(1)-(3)] with the present facility, tests with axisymmetric and discrete compression surfaces, tests with upstream pegs simulating frontal-area blockage of fuel introduced by lateral injection, and analysis of the adiabatic near wake have been reported. At the conclusion of this work, the following facts had been established: a) the base pressure can be raised, by focusing compression waves on the near wake, to levels that provide net thrust on a well designed projectile, b) the length scales of the compression surfaces are imposed on the near wake - a weak optimum is obtained with the compression beginning immediately downstream of the base plane, c) base pressure elevation is significantly reduced with discrete surfaces as opposed to an equivalent axisymmetric surface, d) upstream-radial pegs cause a slight reduction in base pressure and a relatively large shortening of the wake structure, and e) an integral analysis[(4)] agrees reasonably well with experiments for no compression and axisymmetric compression.

Continuing tests have studied cold air injection with radial jets just upstream of the base plane and porous base bleed. This present report describes this continuing work built upon the above foundation.

II. RESULTS

All tests were conducted at a free stream Mach number, upstream of the base plane, of $M_1 = 2.98$. The base diameter was 2.25 inches and the nominal test Reynolds based on the base diameter was 2.7×10^6. The boundary layer momentum thickness at the base plane was computed to be 1.2 percent of the base radius. Details of the test facility are reported in Ref. (1), (2), and (3).

Radial Jet Injection

Cold air was injected through six orifices drilled into the hollow forebody at 60^o intervals around the periphery 0.22 base radii upstream of the base plane. The sonic exit flow discharged normal to the freestream. Two orifice diameters were tested to independently vary injection rate and pressure ratio. Jet penetration height at the Mach disk, computed by the theory of Ref. (5), increased with injection rate from about 0.2 to 0.3 base radii.

The base to free stream static pressure ratio (P_b/P_1) and the jet to free stream stagnation pressure ratio (P_{o_J}/P_{o_1}) are plotted against the injection parameter (the ratio of the jet flow rate to the free stream flow rate through an area equal to the base area) in Figure 1. Results are shown for no compression and for axisymmetric compression with compression section II(2) which produces a net base thrust. The important point is that the base pressure decreases with cold air injection as a result of the competing effects of vortex generation, flow displacement,

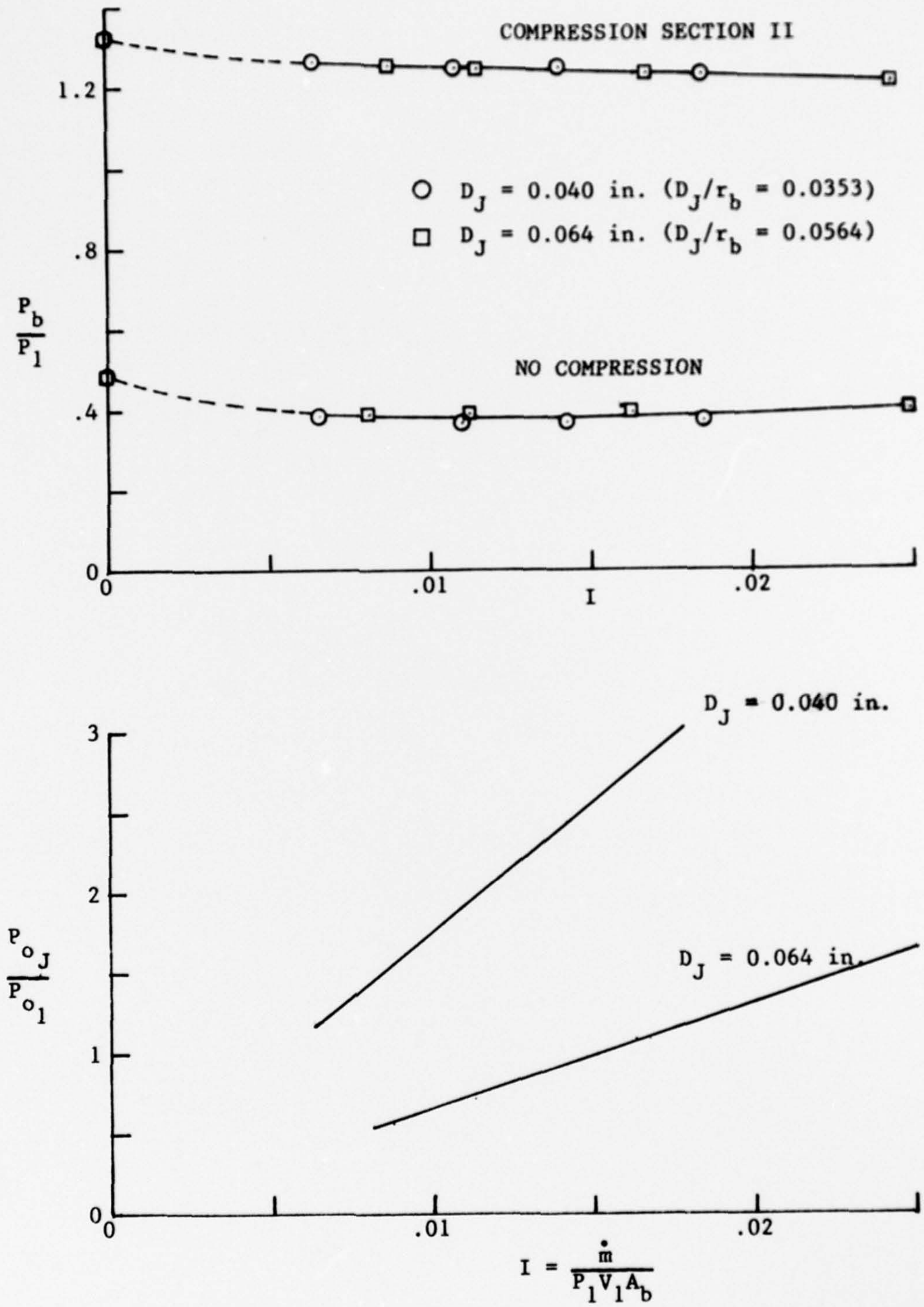


Figure 1. Base Pressure and Jet Nozzle Pressure Ratios for Cold-Air Radial Injection

elevation of the upstream body pressure by the shock system, and a degradation in total pressure by the shock system. This decrease is essentially independent of orifice diameter and reaches a maximum of over 10 percent of the free stream static pressure for both no compression and axisymmetric compression.

The static pressures immediately ahead and behind a radial jet, as important for penetration analysis[5], are presented in Figure 2. For comparison, the static pressure ahead of a radial peg, designed to simulate the frontal area blockage of the radial jet[2], is also shown. (The pressure downstream of the radial peg was not measured.) The upstream pressure for the radial peg is essentially that for two-dimensional, shock-induced boundary layer separation. The additional effect of mass entrainment significantly lowers the upstream pressure for the radial jet. The additive effects of blockage and mass entrainment result in a reducing downstream pressure with increasing injection rate.

Typical pressure and Mach number distributions along the centerline of the near wake with radial injection are compared with those for the clean base in Figure 3. Injection significantly alters the wake structure and causes a large reduction in the wake length scales. The wake changes indicate increased mixing with injection. Figure 4 shows a comparison of wake centerline results with radial injection and with radial pegs designed to simulate the frontal area blockage of the radial jets.[2]. The wake length scales and the base pressures with the radial peg model are reduced relative to those for the clean base[2]. The radial jets cause an additional reduction in the base pressure and, as seen in

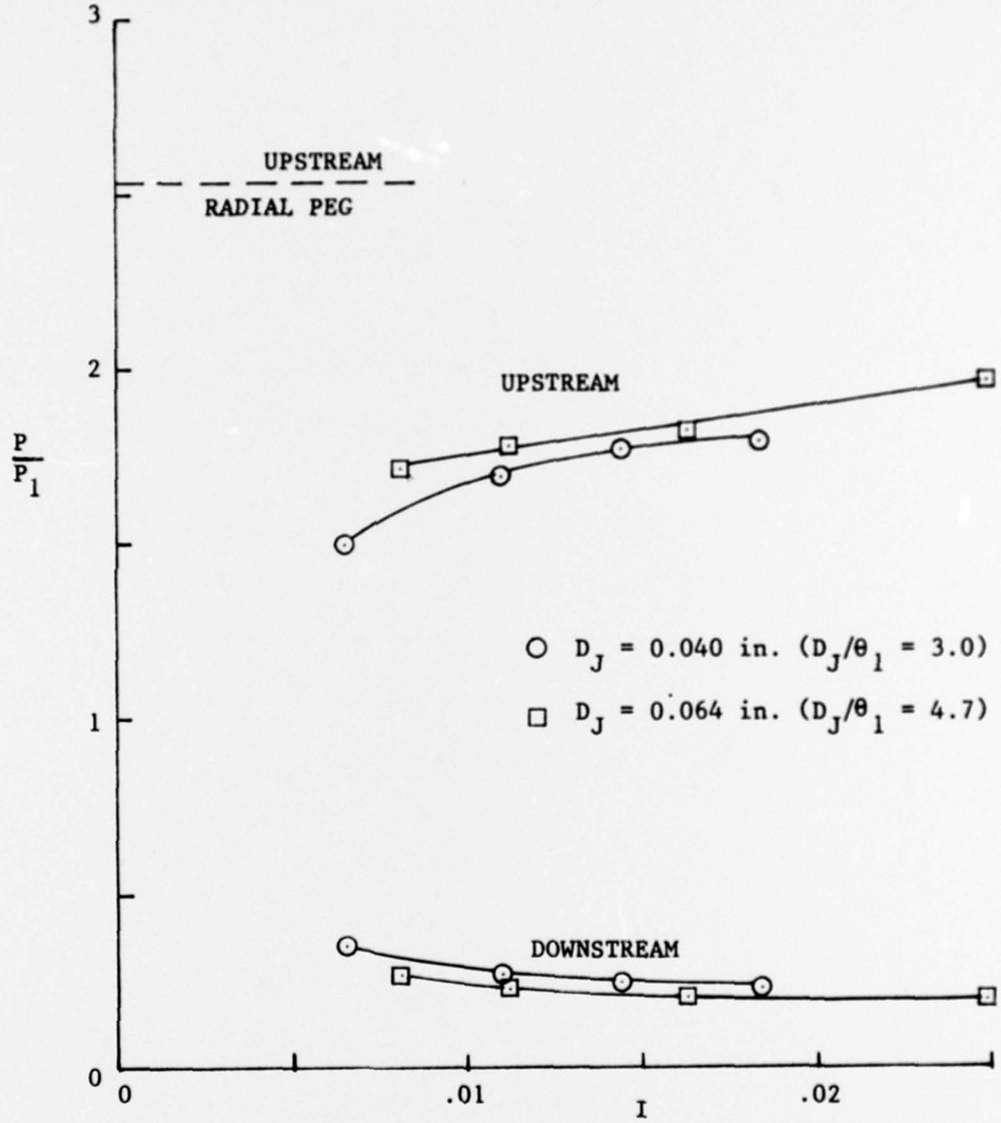


Figure 2. Surface pressures upstream and downstream of a radial jet.

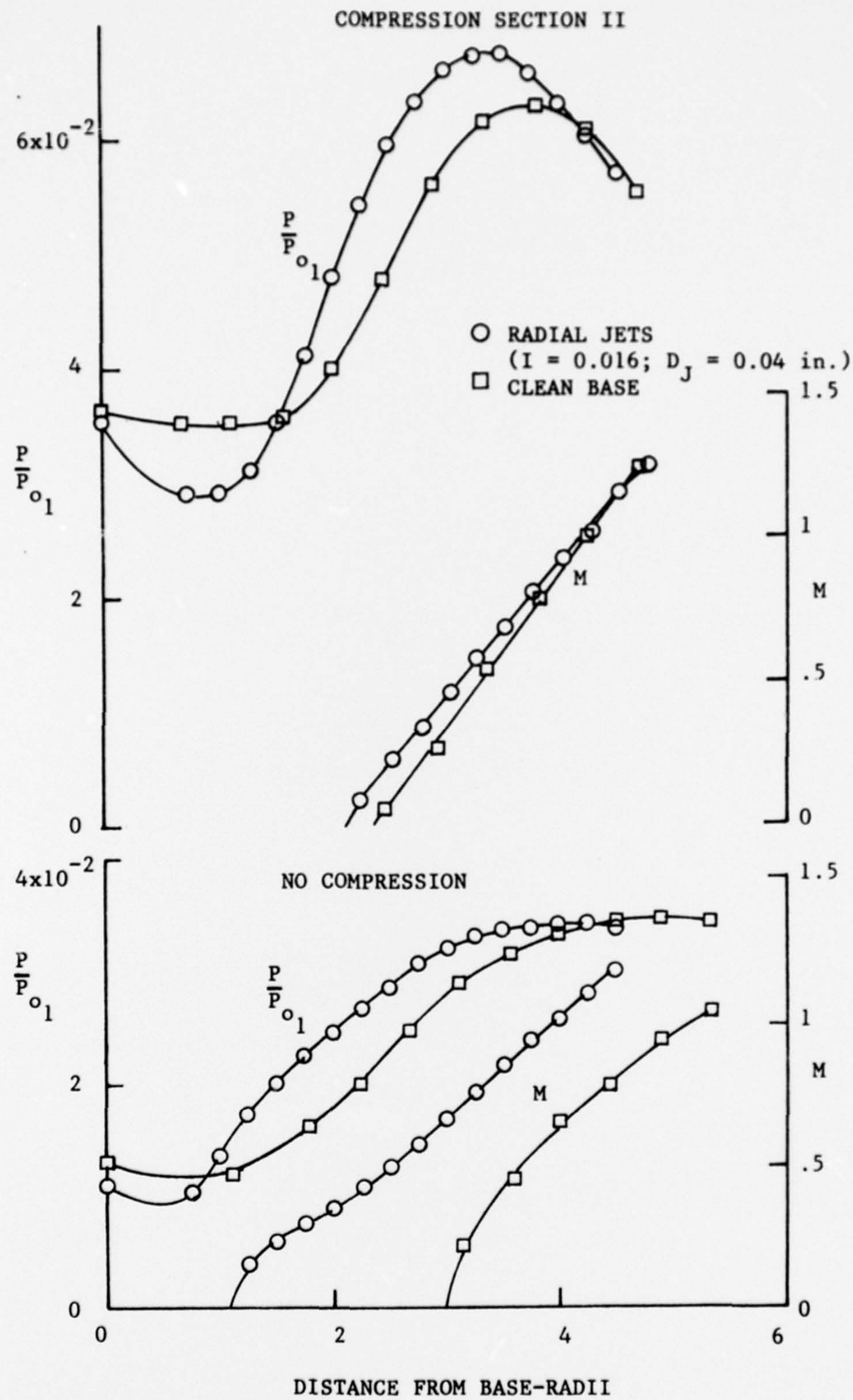
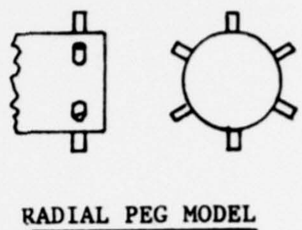


Figure 3. Near Wake Centerline Static Pressure and Mach Number Distributions with and without Radial Injection.



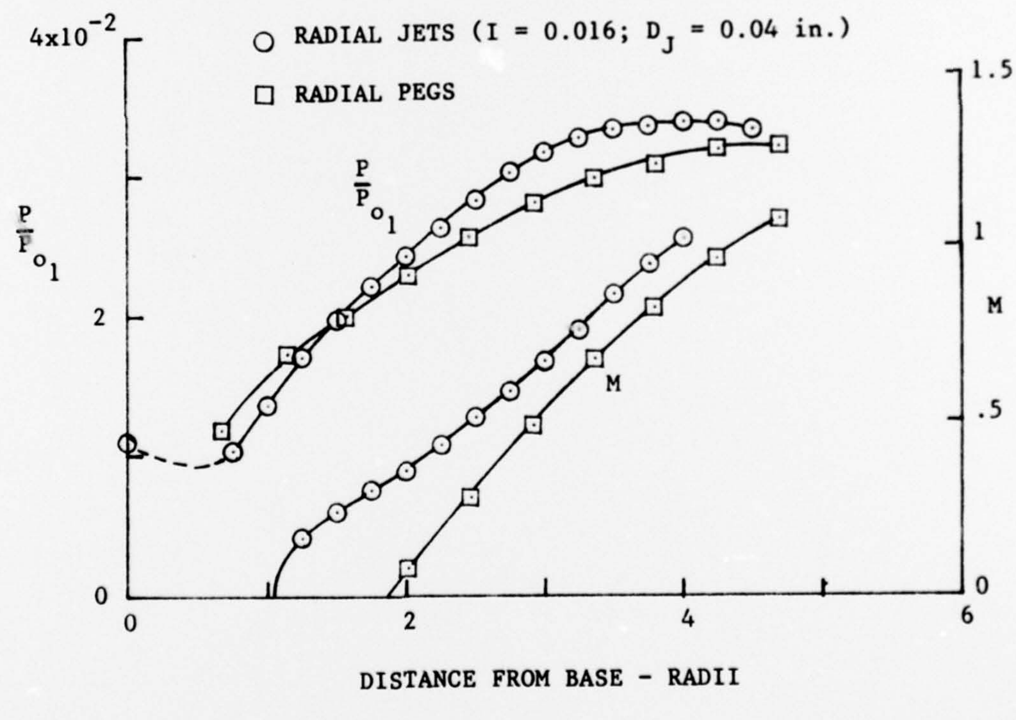


Figure 4. Comparison of Centerline Pressure Mach Number Distributions for Radial Jets and Radial Pegs.

Figure 4, they further shorten the wake even though the injected flow displaces the free stream downstream of the injection point. It is felt that slight flow asymmetries can account for some of the differences in Figure 4 in the low velocity region. However, the important point is that the effects of discrete jet injection is needed in the modelling of the near wake for a real external combustion system.

Near wake Mach number profiles behind a jet and midway between two jets are compared in Figure 5. This comparison demonstrates that the core of the jet does penetrate the near-wake shear layer. The line of maximum velocity difference is indicated on the figure. It seems doubtful, however, that the penetration with this shortened wake is deep enough to significantly alter the temperatures in the regions of flow reversal, and, hence, alter the base pressure by decreased stagnation pressures, if the injected flow is combustible.

Porous Base Bleed

The base injection tests were made with cold air bleed through porous sintered metal. The bore of the cylindrical base model was plugged at the base plane with a 1/16 inch thick sintered metal disk (see the sketch in Figure 6). The base pressures were measured with five flush static pressure taps located in the disk (one at the center and four equally spaced around the periphery at a radius of 0.5 inches). Since these pressure taps were immersed in the injected flow discharging from the porous plug, calibration tests were first made to relate the measured base pressure to an "effective" base pressure, P_{be}. For these calibration tests the sintered metal disc was mounted in a constant diameter tube.

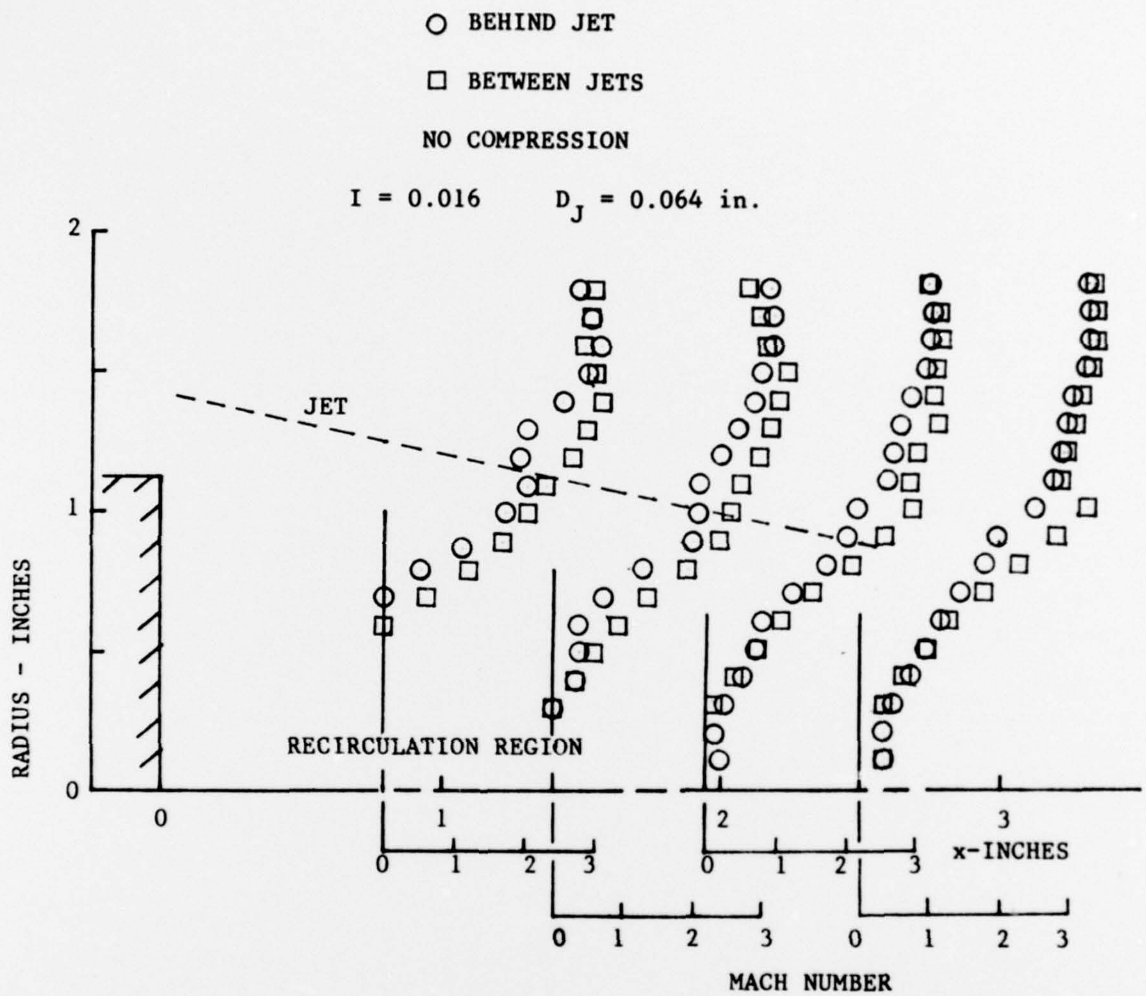
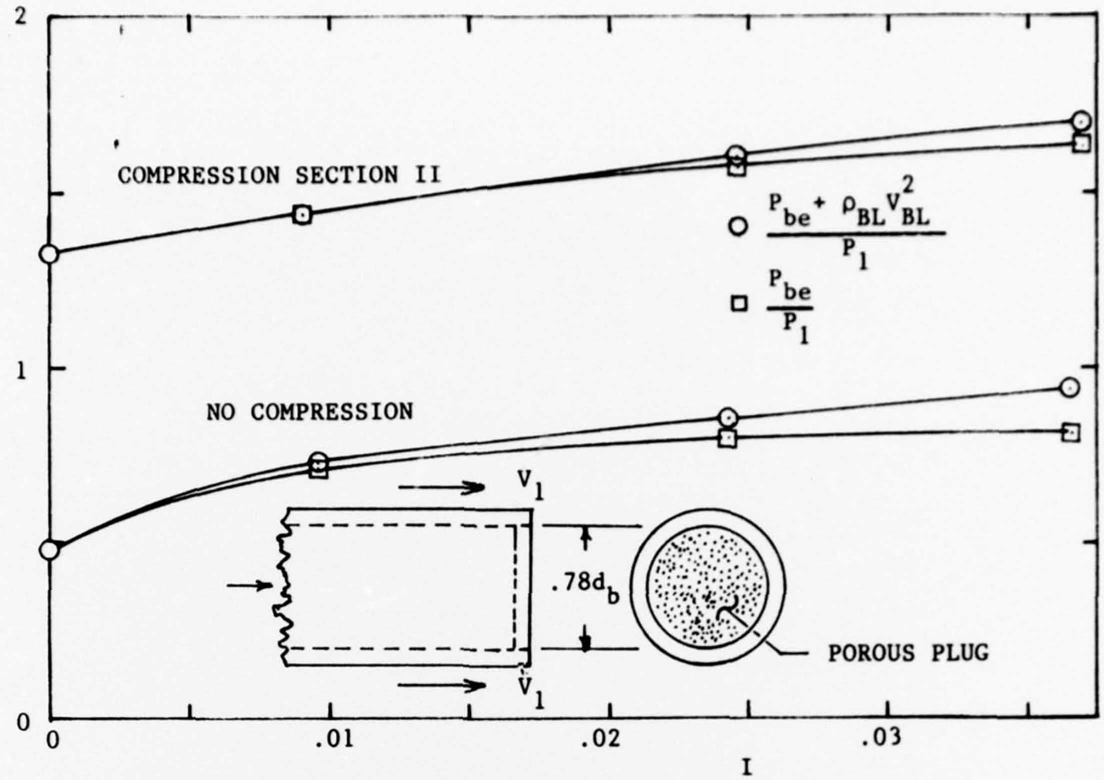


Figure 5. Near Wake Mach Number Profiles With Radial Injection.



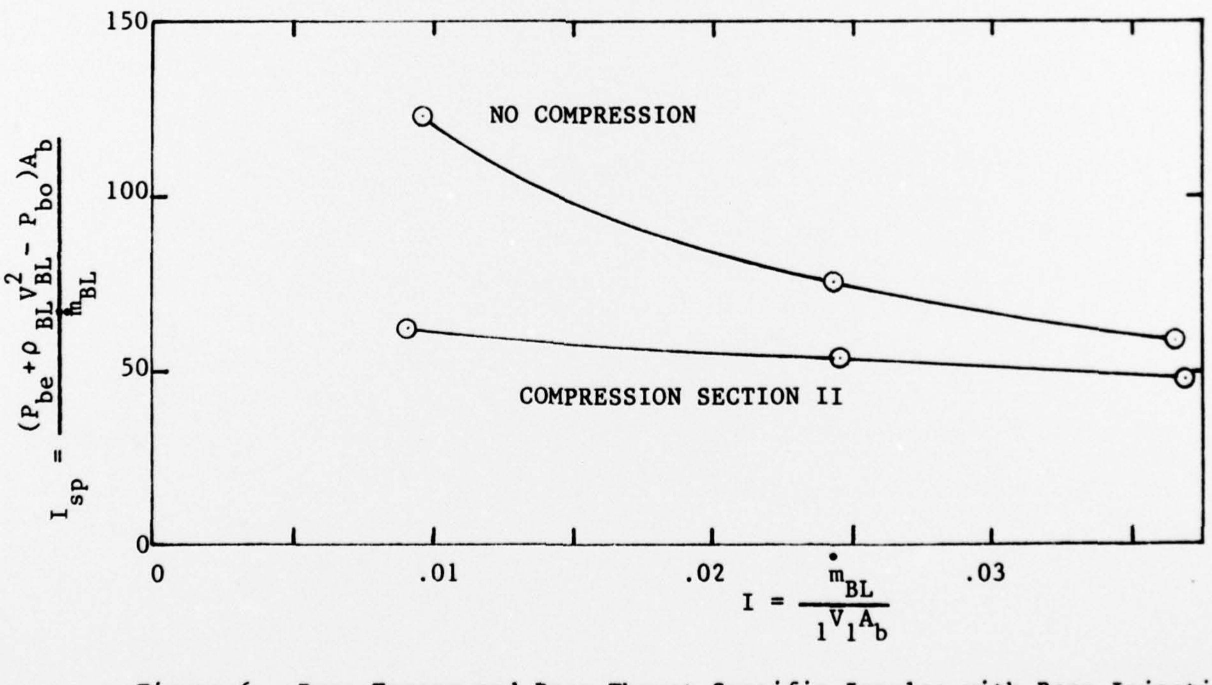


Figure 6. Base Forces and Base Thrust Specific Impulse with Base Injection.

Flow through the tube was metered and the base pressures on the porous plug and the mixed-flow static pressure or effective base pressure was measured downstream. This effective base pressure was then correlated with the measured base pressure and flow rate.

Figure 6 presents the results of the base force data with base bleed. The upper part of this figure shows the effect of the mass injection rate on both the effective base pressure and the net base force per unit area (i.e., the impulse function per unit area or the sum of the effective base pressure and momentum flow rate). Results are shown for no compression and for compression with compression section II which produces base thrust without base injection. At the higher flow rates the bleed flow momentum is significant. In addition, at the highest flow rate, base drag is essentially eliminated for the case of no compression while for the case of compression the elevation in base force is sufficient to completely neutralize drag of a well designed projectile. The rate of increase in the net base force with injection rate decreases with increasing injection rate. Furthermore, compression reduces the rate of increase in the net force with injection rate. These trends are emphasized in the lower part of Figure 6 which shows the specific impulse, I_{SP}, based on the increase in net base force due to injection. P_{bo} is the base pressure for the clean base configuration. The specific impulse decreases with the injection parameter and with compression. The initial rise in base pressure with injection parameter for no compression agrees well with the results of Bowman and Clayden for $M_1 = 2.99$.[6] However, their results, using base nozzle injection, showed a peak base pressure at $I \approx 0.005$.

Static pressure and Mach number distributions along the centerline of the near wake with no compression are shown in Figure 7 for no injection and two values of the injection rate. For the lower injection rate, I = 0.01, the recirculation bubble extends from one to four base radii downstream of the base plane. For the higher injection rate, I = 0.037, the recirculation bubble has been blown off. The primary effect of injection noted here other than the increase in base pressure, is to increase the near-wake length and, correspondingly, reduce the adverse pressure gradients. The simultaneous increase in length and decrease in pressure gradient indicate relatively large reductions in shear stresses acting on the flow along the axis.

The effect of compression on the near-wake centerline pressure and Mach number distributions is illustrated in Figure 8. The control enforced by the compression waves shortens the near wake. Mass addition with compression results in a slight lengthening of the wake and a substantial reduction in the peak over-pressure. Downstream of this peak the flow accelerates rapidly under the favorable pressure gradient due to expansion waves focused on the wake.

Near-wake static pressure and Mach number profiles are shown in Figure 9 for no compression and I = 0.010. A uniform central core of bleed flow fills the base area upstream of the recirculation bubble. The corner expansion is evident in the outer portion of the shear layer. Downstream of the recirculation bubble a developed shear flow is established and the radial pressure gradients are indicative of the recompression curvature. In the plane near the center of the recirculation bubble the radial pressure gradients are small.

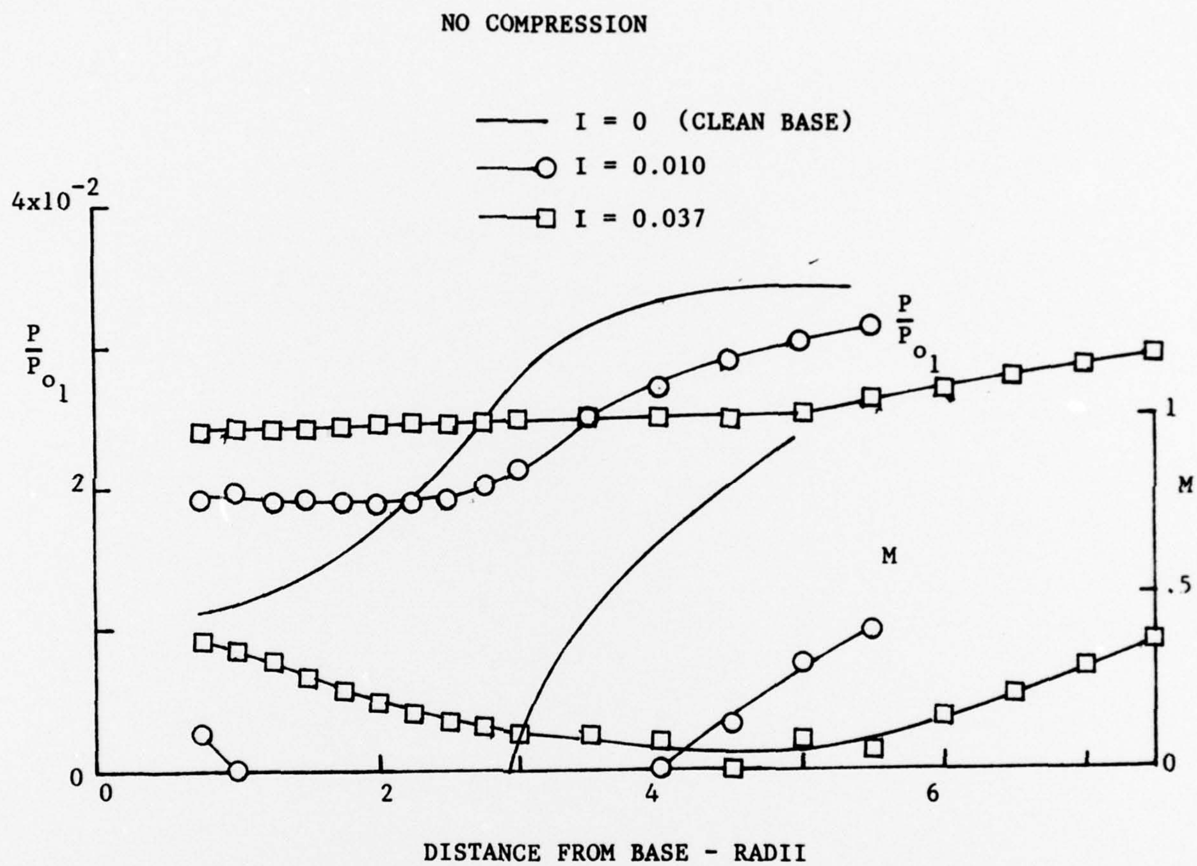


Figure 7. Near Wake Centerline Static Pressure and Mach Number Distributions with and without Base Injection.

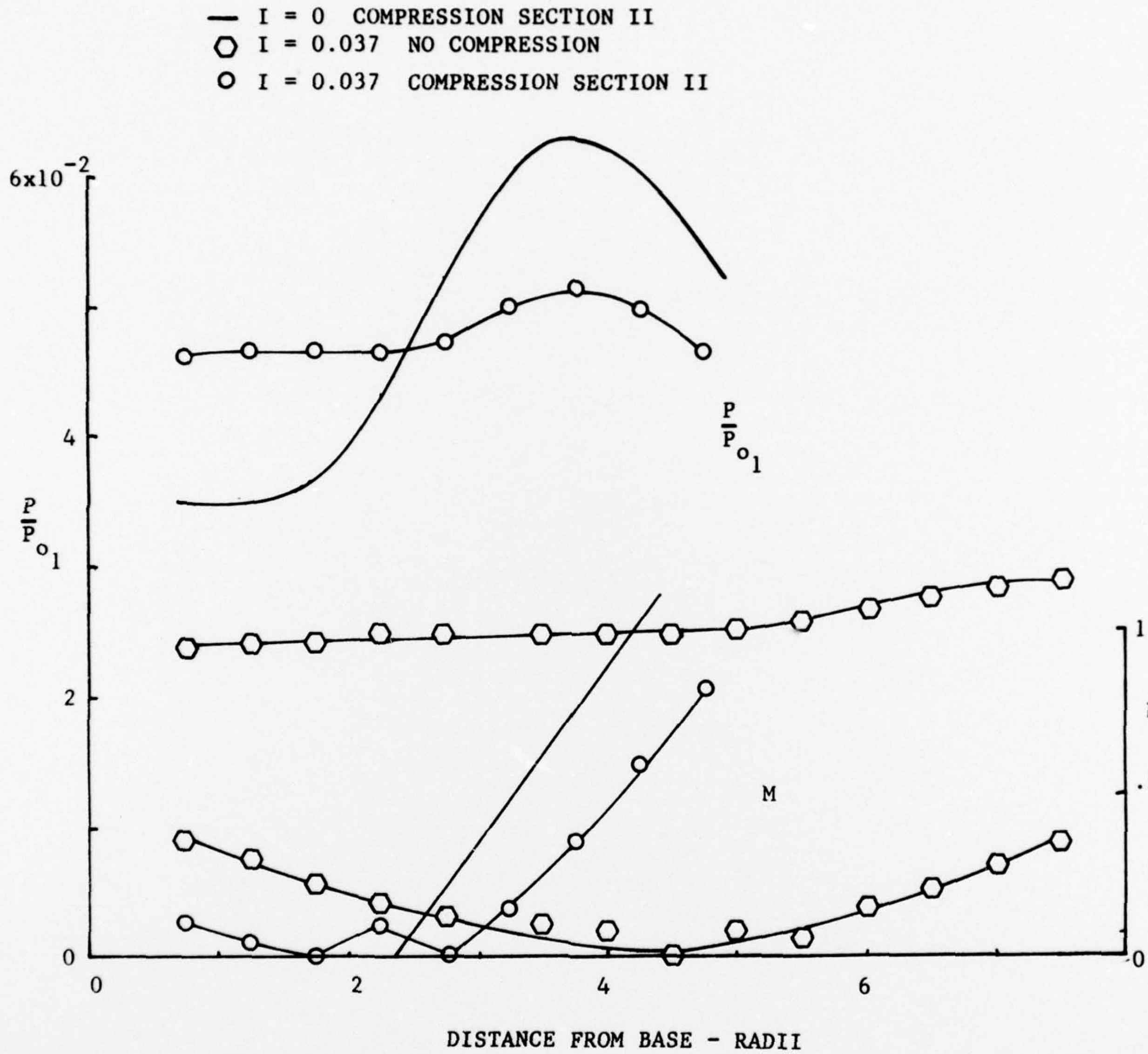


Figure 8. Effects of Compression on Base Centerline Static Pressure And Mach Number Distributions.

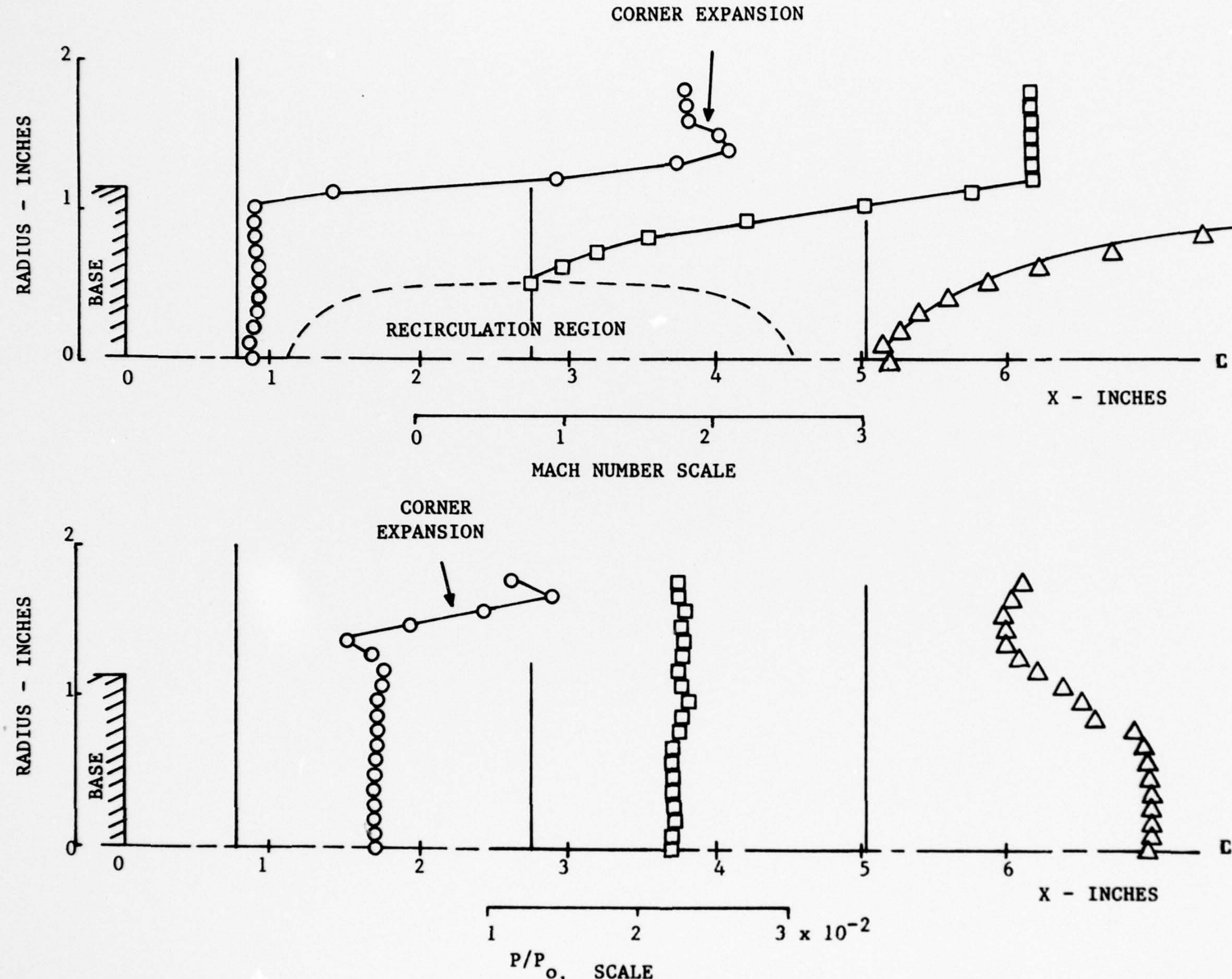


Figure 9. Near Wake Mach Number and Static Pressure Profiles with Base Injection I = 0.010.

III. CONCLUSIONS

Cold air, radial injection tests have shown that discrete jet injection immediately ahead of the base plane significantly alters the wake structure, reduces the wake length scales, and lowers the base pressure. The effects of discrete jet injection must, therefore, be incorporated in a realistic analytical model of the near wake for a real external combustion system. This is exclusive of the degradations due to asymmetric compression as encountered in earlier tests.

Cold air, base injection tests have shown that for porous base bleed and no compression the base force per unit area increases continuously with injection rate to approximately the free stream pressure when the recirculation bubble has been blown off. However, the gain in base force due to base injection decreases with increasing injection rate. Furthermore for a given base injection rate, compression lowers the base force elevation due to injection. Base injection causes large increases in the wake length scales with no compression and slight increases with compression.

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